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Cost and Performance Report

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Multi-Site In Situ Air Sparging

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TECHNOLOGY CERTIFICATION PROGRAM

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LIST OF ACRONYMS

AFB	Air Force Base
AS	Air Station
ASDP	Air Sparging Design Paradigm
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAH	chlorinated aliphatic hydrocarbon
CAS	cometabolic air sparging
cfm	cubic feet per minute
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense, non-aqueous phase liquid
DoD	Department of Defense
DoDHF	Department of Defense Housing Facility
DTW	depth to water
EPA	Environmental Protection Agency
LF	landfill
LNAPL	light, non-aqueous phase liquid
MCAS	Marine Corps Air Station
MCB	Marine Corps Base
MTBE	methyl *tert*-butyl ether
NAPL	non-aqueous phase liquid
NBVC	Naval Base Ventura County
NEX	Naval Exchange
NFESC	Naval Facilities Engineering Service Center
O&M	operation and maintenance
OMB	Office of Management and Budget
OU	operable unit
PCE	tetrachloroethene
POL	petroleum, oil and lubricants
PV	present value
PVC	polyvinyl chloride
scfm	standard cubic feet per minute
SERDP	Strategic Environmental Research and Development Program

LIST OF ACRONYMS (continued)

SF_6	sulfur hexafluoride
SVE	soil vapor extraction
TCE	trichloroethene
TPH	total petroleum hydrocarbons
UST	underground storage tank
VC	vinyl chloride

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Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

Air sparging is a process where air is injected directly into the saturated subsurface to (1) volatilize contaminants from the liquid phase to the vapor phase for treatment and/or removal in the vadose zone, and (2) biodegrade contaminants in the saturated zone via stimulation by the introduction of oxygen. Practitioners have proposed using in situ air sparging to (1) treat contaminant source areas trapped within water-saturated and capillary zones, (2) remediate dissolved contaminant plumes, or (3) provide barriers to prevent dissolved contaminant plume migration. In the mid-1990's, the U.S. Air Force Research Laboratory, Airbase and Environmental Technology Division, Tyndall Air Force Base (AFB) initiated an air sparging project funded by the Airbase and Environmental Technology Division (AFRL/MLQE), the Strategic Environmental Research and Development Program (SERDP), and the U.S. Naval Facilities Engineering Service Center (NFESC). This project was conducted by the authors of this document, with input and review from an expert panel comprised of practitioners, program managers, and members of academia to develop a technically defensible and practicable Air Sparging Design Paradigm.

The use of air sparging has increased rapidly since the early 1990's. It is now likely to be the most practiced engineered in situ remediation option when targeting the treatment of hydrocarbon-impacted aquifers. The feasibility assessment, pilot testing, design, and operation of air sparging systems have remained largely empirical, with variability in approaches by different practitioners. Since the mid-1990's, much research has been devoted to gaining a better understanding of air sparging systems; however, it appears that valuable knowledge gained from these studies has yet to be integrated into practice, and many of the current approaches to feasibility assessment, pilot testing, design, and operation show a lack of appreciation for the complexity of the phenomena and the sensitivity of the technology to design and operating conditions. Development of the Air Sparging Design Paradigm will provide guidelines that will not only result in reduced costs associated with the pilot testing and design of air sparging systems, but will also result in improved performance.

The primary performance objective of this study was to implement the Air Sparging Design Paradigm at a number of existing air sparging sites and determine whether the Design Paradigm was effective at evaluating air distribution and whether other design guidelines were valid. The goal of the project was to modify the Air Sparging Design Paradigm as necessary based on results obtained from the 10 field sites. Field testing at these ten sites has resulted in modifications to the Air Sparging Design Paradigm and the final document was generated at the end of this study.

The pilot test recommended in the Air Sparging Design Paradigm for the Standard Design Approach prescribes a suite of diagnostic tests to assess air distribution. The recommended diagnostic tests include pressure response testing, deep vadose zone helium tracer testing, and dissolved oxygen monitoring. Data collected for this study has emphasized the necessity of a suite of diagnostic tests, rather than a reliance on one type of testing. The diagnostic tests also proved useful to evaluate existing systems in terms of their effectiveness at treating the target treatment zone. Three of the sites investigated had air sparging systems that were not impacting the entire target treatment zone and therefore were operating inefficiently. Conversely, the air

sparging system installed at Cape Canaveral AS, FL was shown to be functioning efficiently and as designed.

The Standard Design Approach recommended in the Air Sparging Design Paradigm prescribes a 15-ft well spacing. At all sites were a zone of influence was determined, this well spacing would have been sufficient to achieve adequate treatment of the target treatment zone. At the majority of sites, air was observed to impact groundwater within a small radius around the injection well.

During field testing, the authors observed that many existing air sparging systems were poorly instrumented and monitored. Based on this work and other experience, it is not unreasonable to conclude that a significant fraction of existing air sparging systems are improperly instrumented and monitored, which will result in poor performance and ultimately higher remedial costs.

The total cost for the demonstration at the only full-scale air sparging system installed as part of this project (Port Hueneme, CA) was \$189,880, at a cost of \$130/yd^3 (\$170/m^3). For a real-world implementation at the same site, the total cost to operate the air sparging system for a two-year period is \$259,340 at a cost of \$170/yd^3 (\$230/m^3). Costs for a real-world implementation are higher due to longer operation and higher labor costs. A cost analysis demonstrates that the installation and operation of soil vapor extraction in conjunction with air sparging will have the most significant cost impact. SVE systems have often been routinely installed with air sparging systems, whether or not receptors are at risk. Secondly, the costs associated with long-term monitoring can have a significant cost impact and outweighs the costs associated with the installation of additional injection wells. Higher capital costs associated with air injection wells will likely be offset by shorter clean-up times.

For remediation of a gasoline source zone, thermal treatment is a likely alternative after air sparging. In comparison to thermal treatment systems, air sparging systems offer both lower capital costs and lower costs associated with operation and maintenance. However, the total remediation time for operation of an air sparging system is likely to be longer than that quoted for thermal treatment systems.

Results from this study have been used to finalize the Air Sparging Design Paradigm. Implementation of the Air Sparging Design Paradigm in the evaluation and design of air sparging systems will likely result in air sparging applications that are more cost-effective and in applications that have a better performance record.

2.0 TECHNOLOGY DESCRIPTION

2.1 DESCRIPTION

Air sparging is a process where air is injected directly into the saturated subsurface to (1) volatilize contaminants from the liquid phase to the vapor phase for treatment and/or removal in the vadose zone, and (2) biodegrade contaminants in the saturated zone via stimulation by the introduction of oxygen. Which mechanism accounts for the greater amount of contaminant removal depends on the chemical properties, contaminant distribution, duration of air injection, and soil properties. Generally, volatilization dominates when systems are first turned on and, for aerobically degradable compounds, biodegradation will dominate in later phases of treatment. Volatilized contaminants may be biodegraded in the vadose zone, or may be extracted and treated or discharged, depending on regulatory requirements.

The term biosparging is frequently used to refer to certain types of air sparging systems. There is no clear cut difference between biosparging and air sparging; however, when the term biosparging is used, it usually means that the intent of the operator is to stimulate biodegradation rather than volatilization, typically by using lower air injection rates. For heavier-molecular-weight, non-volatile contaminants, biosparging may be the only approach possible. In addition, many practitioners use the term biosparging to refer to systems that lack soil vapor extraction for vapor collection, since the object is to stimulate biodegradation either in the saturated zone or the unsaturated zone, but before vapor emission.

Practitioners have proposed using in situ air sparging to (1) treat contaminant source areas trapped within water-saturated and capillary zones, (2) remediate dissolved contaminant plumes, or (3) provide barriers to prevent dissolved contaminant plume migration. Most practitioners advocate targeting the source zone for remediation of petroleum-contaminated aquifers, and air sparging is one of the most effective submerged source zone treatment technologies. In the case of most petroleum hydrocarbons, if the source zone can be remediated, then the remaining dissolved plume rapidly dissipates due to natural processes. There may be occasions, however, when plume remediation is warranted. This might be the case when one needs to prevent against further migration of a recalcitrant chemical like trichloroethene (TCE) or methyl *tert*-butyl ether (MTBE).

The use of air sparging has increased rapidly since the early 1990's. Based on informal surveys of underground storage tank (UST) regulators, it is now likely to be the most practiced engineered in situ remediation option when targeting the treatment of hydrocarbon-impacted aquifers. The feasibility assessment, pilot testing, design, and operation of air sparging systems has remained largely empirical, with variability in approaches by different practitioners (Bruell et al., 1997; Johnson et al., 1993; Johnson et al., 1997; U.S. Environmental Protection Agency [EPA], 1992). Since the mid-1990's, much research has been devoted to gaining a better understanding of air sparging systems; however, as discussed in Johnson et al. (2001), it appears that valuable knowledge gained from these studies has yet to be integrated into practice, and many of the current approaches to feasibility assessment, pilot testing, design, and operation show a lack of appreciation for the complexity of the phenomena and the sensitivity of the technology to design and operating conditions.

In the mid-1990's, the U.S. Air Force Research Laboratory, Airbase and Environmental Technology Division, Tyndall AFB initiated an air sparging project funded by the Airbase and Environmental Technology Division (AFRL/MLQE), SERDP, and the U.S. NFESC. This project was conducted by the authors of this document, with input and review from an expert panel comprised of practitioners, program managers, and members of academia. Under this project, both laboratory- and field-scale experiments were conducted, and the results of the individual studies have been, and continue to be reported elsewhere (Amerson, 1997; Amerson et al., 2001; Bruce et al., 1998; 2001; Johnson et al., 1999; Rutherford and Johnson, 1996). The ultimate goal of this project, however, has been the development of a technically defensible and practicable air sparging Design Paradigm.

2.2 PROCESS DESCRIPTION

A typical air sparging system is shown in Figure 1. The major components of a typical air sparging system are shown, including an air injection well, an air compressor or blower to supply air, monitoring points and wells, and an optional vapor extraction system.

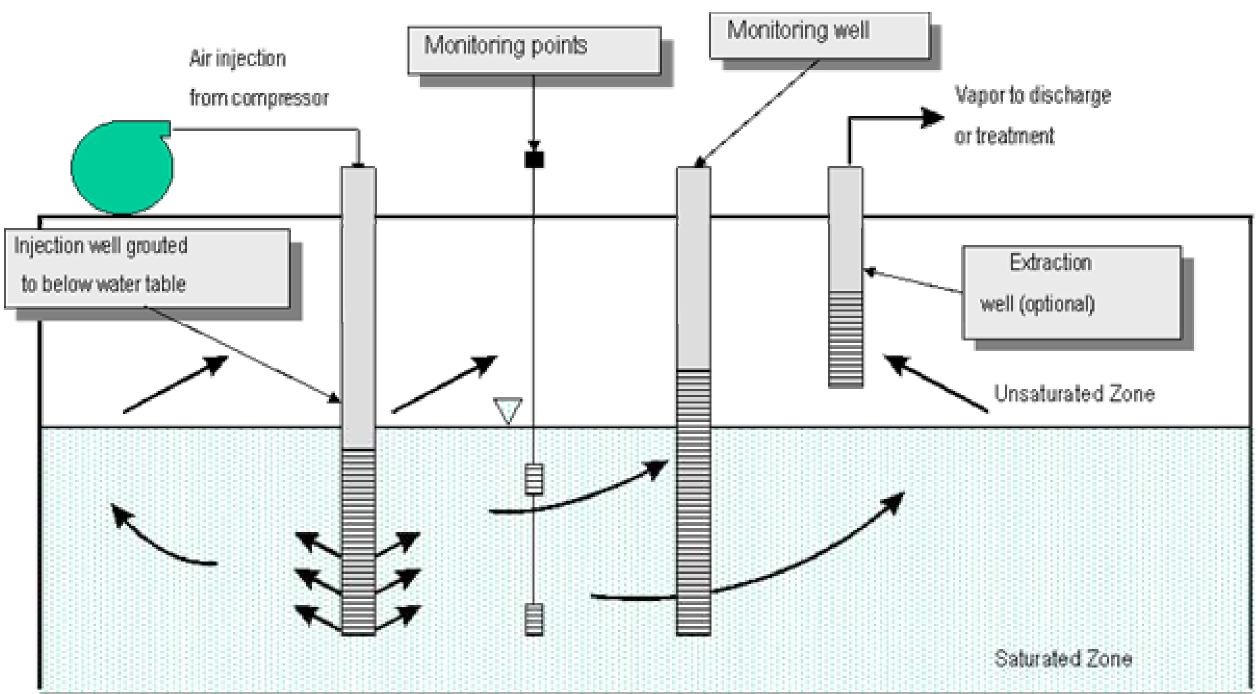

Figure 1. Schematic Diagram of a Typical Air Sparging System.

The air injection wells generally are vertical and are screened at depths located below the contamination level. The wells are grouted to depths below the water table to prevent short-circuiting of air through a sand pack into the vadose zone (Figure 2). If the medium is homogenous sand (Figure 3), the airflow will be relatively uniform around the air injection well, resulting in good mass transfer. In contrast, a heterogeneous medium may result in non-uniform

and confining airflow thus reducing air sparging effectiveness (Figure 3). In practice, all sites have some degree of soil heterogeneity and nonuniform air flow is common. The practitioner must ensure that the nonuniformity of air flow is acknowledged and accounted for in system design. In situations where the contaminated subsurface is under buildings, runways, or other structures through which well installation is impossible, horizontal or inclined air injection wells may have to be considered.

Compressors or blowers are needed to supply air to the injection wells. The selection of a compressor or blower depends upon site-specific characteristics that dictate air flow and pressure requirements. The monitoring points and related equipment are needed to provide information on compressor air flowrates and pressure, and contaminant concentrations in the groundwater, soil, and effluent air stream to analyze the progress of the remediation. In some air sparging systems, an optional vapor extraction well is installed to transfer contaminated vapor from the vadose zone for treatment and or emission to the atmosphere.

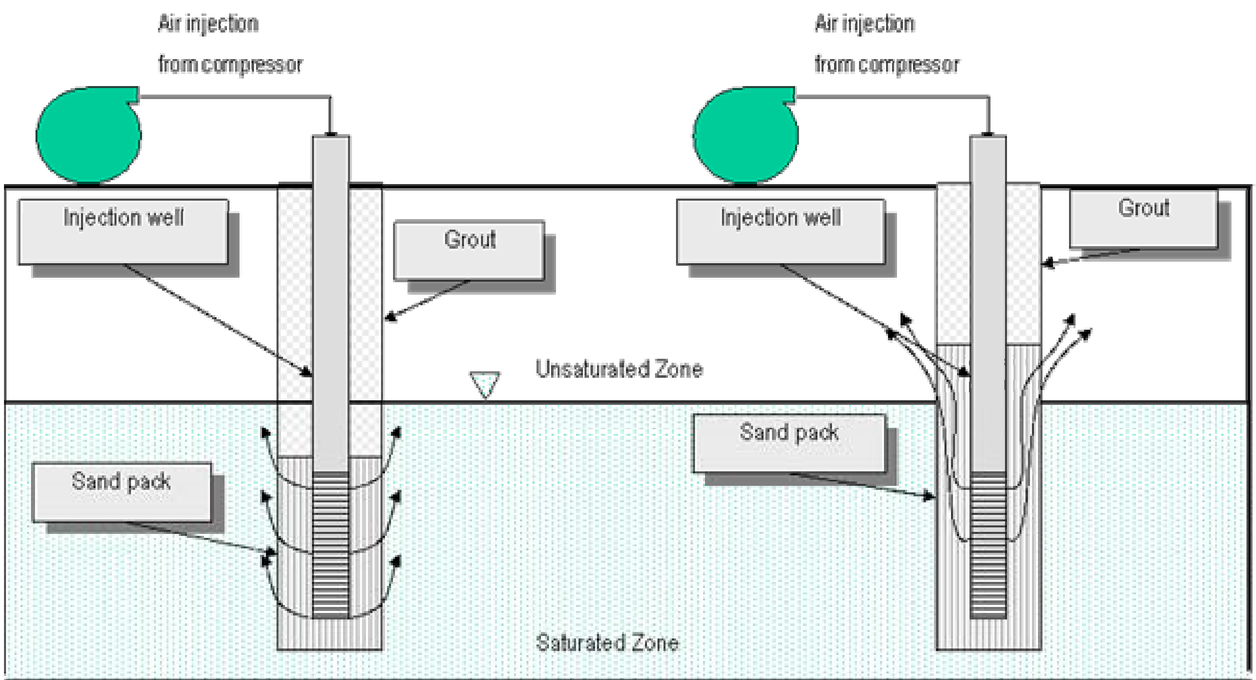

Figure 2. Construction Details and Air Flow Patterns of an Air Sparging Well Grouted Below and Above the Water Table.

Unique design criteria for the air sparging technology as prescribed by the Air Sparging Design Paradigm are evident during pilot testing, system design, and system monitoring as follows:

- Pilot testing
  - Determine affordable well spacing based on site budget.
  - Evaluate air distribution.
  - Look for problems with air distribution.

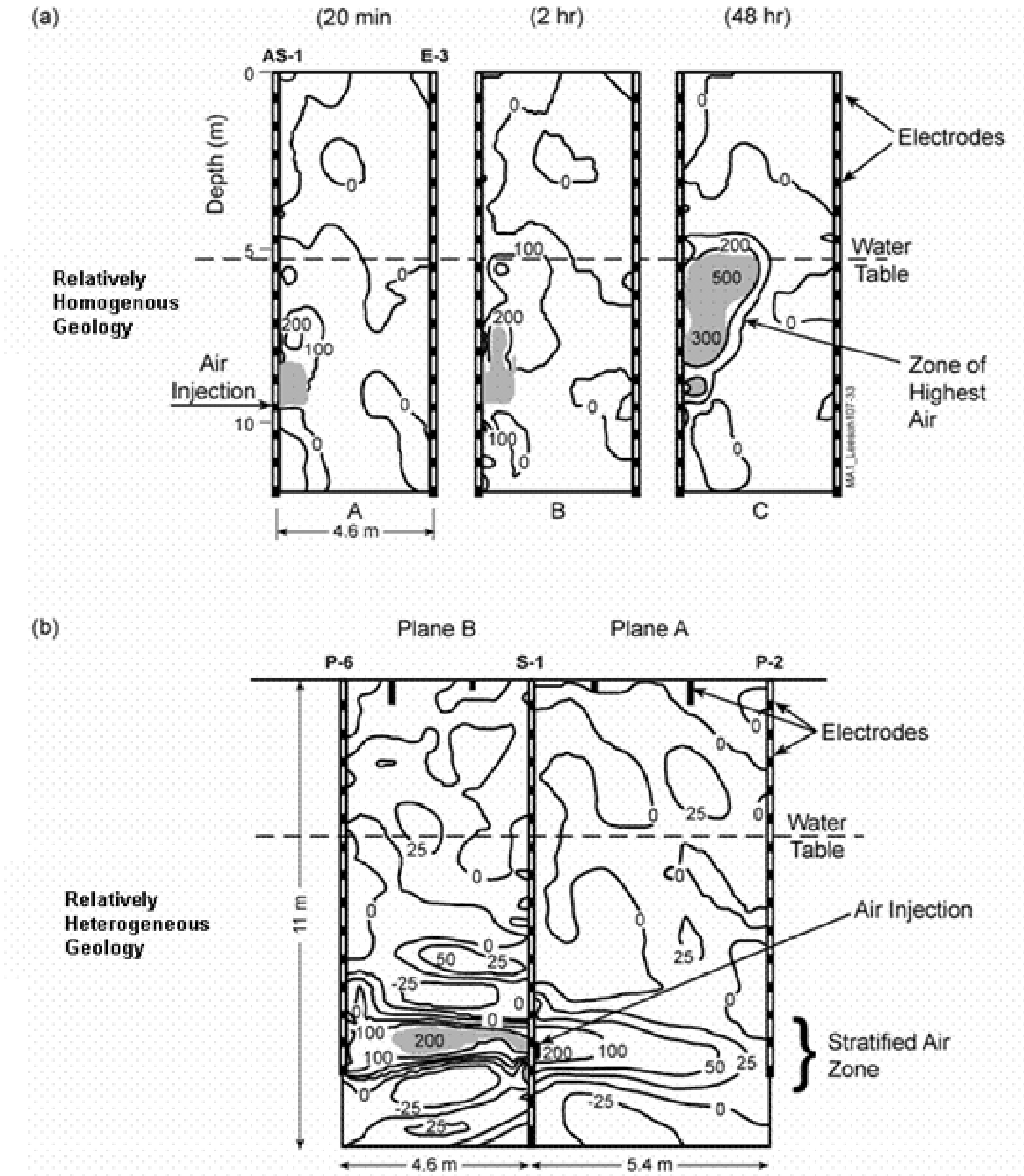

Figure 3. Air Flow Patterns When Sparging in a (A) Homogeneous or (B) Heterogeneous Soil Structure.

- System design
  - Select well spacing: standard or site-specific approach.
  - Determine air flow system.

- System monitoring
  - Use of discrete groundwater sampling points.

The air sparging pilot test has been significantly streamlined to evaluate a small number of key parameters that would indicate whether air sparging is feasible. This differs from the traditional approach where pilot testing was used to attempt to determine design parameters for scale-up. Research demonstrated that a short-term pilot test is not sufficient to provide a good indicator of the long-term performance of an air sparging system; however, it can provide information on whether there are difficulties with air distribution and therefore with successful air sparging.

The system design itself then also has been streamlined, recognizing the fact that air distribution can be problematic and difficult to delineate with any degree of confidence. The practitioner is advised therefore, to use a small well spacing to provide the maximum air to contaminant contact. This has been termed the Standard Design Approach where a 15-ft well spacing is implemented. The Site-Specific Design Approach is for practitioners with large sites who need to reduce costs associated with well installation. At these sites, more careful evaluation of air distribution is recommended to ensure larger well spacings are feasible. Also as part of the system design, pulsed operation of banks of two to five injection wells for four reasons: a) the difficulty of controlling a multi-well air injection system increases as the number of wells manifolded together increases, b) the required system injection flow capacity is lower in this mode, c) studies suggest that performance can be improved by operating in a pulsed mode, and d) pulsed operation may be necessary in air sparging barrier applications to prevent groundwater bypassing due to water relative permeability reductions caused by air injection (Johnson, 2001).

System monitoring is accomplished from monitoring individual rotameters on each air injection well, and using discrete level groundwater monitoring points to measure groundwater contamination. Soil gas monitoring points can also be used for contaminant measurements in addition to tracer measurements.

Air sparging has been demonstrated to be very effective at contaminant reduction, both for petroleum hydrocarbons and chlorinated solvents. A combination of volatilization and biodegradation allow for removal of many compounds to below detection limits. Historically, many sites have shown significant rebound of contaminant concentrations after conducting air sparging. The cause of this appears to be primarily due to poor monitoring techniques that indicated the site was clean. Improved monitoring techniques such as the discrete sampling from groundwater monitoring points should alleviate this problem; however, it is recommended that sites continue to be sampled for at least one year after discontinuing air sparging.

Personnel and training requirements for the air sparging technology are relatively simple. A field technician capable of performing weekly system checks to verify air flowrates and proper operation of the system compressor is sufficient. Compressors will require periodic maintenance, but can generally operate for several years before replacement is necessary. Maintenance of compressors is specific to the compressor and guidance should be sought from the manufacturer. Health and safety requirements also are minimal, unless subsurface structures or buildings are within the zone of influence of the air sparging system. In these situations, care must be taken that vapors are not pushed into these structures, potentially causing explosive or toxic environments.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

While air sparging has a number of advantages over competing technologies, the technology is not without limitations. Listed below are a number of advantages and limitations of air sparging.

Advantages of Air Sparging

- Since only readily available commercial equipment is utilized (i.e. polyvinyl chloride [PVC] well casing, compressors or blowers, etc.), air sparging is a simple and low cost technology to implement. The equipment is easy to install and causes minimal disturbance to site operations.
- Once the system is installed at a site, it requires minimal operational oversight relative to soil vapor extraction (SVE) systems, which demand extensive monitoring.
- There are no waste streams generated that require treatment because the exiting air stream can be vented directly to the atmosphere.
- At sites where smear zone contamination has developed due to a fluctuating water table, air sparging is effective at treating the smear zone since air moves vertically upward through this region.
- The technology is effective in treating source area contamination, thereby limiting off-site migration of dissolved contaminants.
- The technology is compatible with other remediation technologies such as SVE and bioventing.
- Because biodegradation is a component of the air sparging process, this technology has the potential to mineralize contaminants rather than simply transferring contaminants to another medium.

Limitations of Air Sparging

- The technology is not suitable for treating contaminants with low values of Henry's Law constants or low volatility unless the compound is aerobically biodegradable. Semi-volatile contaminants with low aerobic biodegradability are not treated effectively with air sparging.
- Sites that contain contaminants that can be removed effectively via biodegradation, but not volatilization, were remediated slowly due to relatively slow biodegradation rates.
- Site geological conditions such as stratification, heterogeneity, and anisotropy, will prevent uniform air flow through the medium to reduce air sparging effectiveness.
- Free product (nonaqueous phase liquids [NAPL]) in large quantities may come in limited contact with the injected air. This may be a particular concern with dense nonaqueous phase liquids (DNAPLs) that will sink to the bottom of the aquifer, thereby limiting the effectiveness of air sparging.
- There is a potential for migration of volatilized contaminants into buildings and other structures (accounting for vapor migration in system design can often alleviate this problem).
- When air sparging is applied to contain a dissolved phase plume, a zone of reduced hydraulic conductivity could form and, if not managed properly, could allow the plume to circumvent the zone of air sparging influence.
- Air flow is effective over a defined area, possibly requiring a large number of wells to obtain adequate air flow through the contaminated region.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary performance objective was to implement the Air Sparging Design Paradigm at a number of existing air sparging sites and determine whether the Design Paradigm was effective at evaluating air distribution. The goal of the project was to modify the Air Sparging Design Paradigm as necessary based on results obtained from the 10 field sites.

3.2 SELECTION OF TEST SITES

Ten field sites were selected for study. The criteria used to select the test sites were as follows.

- Various soil types (i.e. site with sandy soils compared to sites with predominantly clayey soils).
- Various contaminants (i.e. petroleum hydrocarbons or chlorinated solvents).
- Willingness of Base personnel to allow testing at their site.
- Air sparging equipment in place:
    - Air delivery system.
    - Vapor extraction system.
    - Sparge wells.
    - Groundwater monitoring wells.
- Proper design of the equipment:
    - Sparge well screen interval starts below 5 ft, but no more than 10 ft under the groundwater table.
    - Sparge wells grouted beneath the groundwater table.
    - Soil vapor extraction well capable of capturing 80% of the injection air.
    - Air compressor or blower capable of delivering 5 to 20 cubic feet per minute (cfm) into the sparge well.

3.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

Ten test sites were selected for testing and/or evaluation. Table 1 lists the site characteristics including site name, former role of the site, type of air sparging system installed, soil type, depth to groundwater, and contaminant type and concentration.

3.4 PHYSICAL SET-UP AND OPERATION

Existing sites were selected for evaluation. At five sites, no additional monitoring devices were installed (Camp Lejeune, Camp Pendleton, Hill AFB, McClellan AFB, and Novato). At three sites, groundwater and soil gas monitoring points were installed (Cape Canaveral AS, Fairchild

Table 1. Site Characteristics.

Installation	Site Name	Site History	Type of System	Soil Type	Depth to Groundwater	Contaminant Type	Contaminant Concentration
Eielson AFB, AK	ST10/SS14	POL yard & landfill	Bioventing; can inject below water table	Sandy loam soil; sand & gravel below	8 ft	BTEX, anthracene, & naphthalene in groundwater	Benzene up to 460 µg/L in groundwater
NBVC, Port Hueneme site, CA	NEX Gasoline Station	Gasoline Station	Full-scale sparging, based on ASDP	Fine to coarse sand	8 ft	BTEX & MTBE	Benzene (39 mg/L) & MTBE (10 mg/L)
Cape Canaveral AS, FL	FT-17 (CCFTA-2)	Firefighter Training Area	Horizontal well	Sand	6 ft	Vinyl chloride	VC up to 4,000 µg/L in groundwater
Fort Lewis, WA	LF4	Landfill	Air sparge/SVE curtain	Outwash sands & gravels, glacial till	30-35 ft	TCE, DCE, & VC in groundwater	TCE (150 µg/L), DCE (12 µg/L), VC (7.8 µg/L)
Fairchild AFB, WA	FT-1	Firefighter Training Area	Air sparging curtain	Silty sands & gravels	3-7 ft	BTEX, CAHs in groundwater	Total BTEX up to 1,320 µg/L in groundwater
Marine Corps Base Camp Lejeune, NC	LCH-4015	Gasoline station, fuel farm	Full-scale air sparging system	Fine sand to sandy clay	3-5 ft	Benzene, ethylbenzene, xylenes, MTBE	Benzene (10,600 µg/L), ethylbenzene (2,960 µg/L), total xylenes (9,960 µg/L), MTBE (256 µg/L)
Marine Corps Base Camp Pendleton, CA	MCAS Fuel Farm	Air Station Fuel Farm	Full-scale sparging, based on ASDP	Sand & silty sand	4-15 ft	TPH, BTEX	TPH up to 27 mg/L
DoD Housing Facility Novato, CA	Site 957/970	PWC service station USTs	Hot spot removal by sparging & SVE	Sand, gravel, & clay	3-13 ft	TPH, BTEX, MTBE	TPH (>100,000 µg/L), Benzene (>1,000 µg/L), MTBE (>30,000 µg/L)
McClellan AFB, CA	OU A	Industrial degreasing facility	CAS pilot demonstration	Sand & gravel aquifer	110 ft	PCE & daughter products, DCA	TCE (>1,000 µg/L), DCE (88 µg/L)
Hill AFB, UT	OU-6	UST	Pilot study	Sands & silty sands	100 ft	TCE	440 µg/L

AS = Air Station; ASDP = Air Sparging Design Paradigm; BTEX = benzene, toluene, ethylbenzene, and total xylenes; CAH = chlorinated aliphatic hydrocarbon; CAS = cometabolic air sparging; DCE = dichloroethene; NEX = Naval Exchange; NVBC = Naval Base Ventura County; PCE = tetrachloroethene; POL = petroleum, oil and lubricants; TPH = total petroleum hydrocarbon; VC = vinyl chloride.

AFB, and Fort Lewis). At Eielson AFB, an air injection well was installed in addition to groundwater and soil gas monitoring points. At the Construction Battalion Center (CBC) Port Hueneme, additional air injection wells were installed to bring the existing pilot-scale system up to a full-scale system; however, the current system was well-monitored and no additional monitoring devices were installed. The configuration, depth, and installation methods varied from site to site. More detailed descriptions of the site installations are provided in the Final Report.

3.5 SAMPLING/MONITORING AND ANALYTICAL PROCEDURES

Sampling and monitoring procedures varied depending on site conditions and configuration. However, the following general guidelines were followed for every site. Table 2 identifies the activities that were conducted at each site. The Final Report provides additional detail about the procedures performed at each site. A summary of the activities conducted at the sites is provided in the following sections.

Table 2. Summary of Activities Conducted at each Site.

Site	System	DTW (M)	Tests Completed
Eielson AFB, AK	IAS	20	P, He, SF_6, P/P
Port Hueneme, CA	IAS	3	P, SF_6, P/P
Fort Lewis, WA	IAS/SVE	20	P, He, SF_6
Fairchild AFB, WA	IAS	2	P, He, SF_6
Cape Canaveral AS, FL	IAS	1	P, He, SF_6, P/P
Camp Lejeune, SC	IAS/SVE	1	P
Camp Pendleton, CA	IAS	3	P, He
DoDHF Novato, CA	IAS/SVE	25	P
McClellan AFB, CA	IAS/SVE	20	P, SF_6
Fairchild AFB, WA	IAS	2	P, He

DTW = depth to water; IAS = in situ air sparging; P = pressure testing; He = helium tracer testing; SF6 = sulfur hexafluoride tracer testing; P\P = push-pull test.

3.5.1 Base-Line Monitoring

Base-line monitoring generally included measuring groundwater/light nonaqueous phase liquid (LNAPL) levels; dissolved oxygen in groundwater; oxygen, carbon dioxide, and total petroleum hydrocarbon (TPH) concentrations in the vadose zone; and mass transfer rate assessments.

The depth to groundwater and apparent thickness of LNAPL in site wells were measured with an oil/water interface probe (ORS Model #1068013 or equivalent). The probe lead was a 50- to

200-ft measuring tape with 0.01-ft increments. The interface probe distinguishes between polar and nonpolar fluids in the well. The probe gives a solid tone when it encounters a nonpolar liquid (LNAPL) and a constant beep when it encounters a polar liquid (water).

Groundwater samples were collected using a low-flow peristaltic pump. Samples were measured for dissolved oxygen content under continuous flow using a dissolved oxygen meter (YSI Model 5776 Oxygen Probe or similar). In order to minimize aeration of the sample, a continuous flow-through cell was used to provide a sampling chamber for the meter. A sufficient volume of water from the well or groundwater sampling point was purged before sample collection to ensure that a sample representative of the formation is obtained.

The purpose of soil gas testing is to determine baseline contaminant vapor concentrations in the vadose zone. In addition, contaminant concentrations were monitored during field testing. Soil gas was extracted from the vadose zone with a soil gas sampling pump system. Gaseous concentrations of carbon dioxide, oxygen, and TPH were analyzed using a GasTech Series Gas Monitor Model GT205 or equivalent. A digital display displays the soil gas concentrations within the sample instantaneously. The battery charge level on the GT205 was checked to ensure proper operation. The air filters were checked and, if necessary, were cleaned or replaced before sampling is started. The instrument were turned on and equilibrated for at least 10 minutes before conducting calibration or obtaining measurements. The sampling pump of the instrument was checked to ensure that it is functioning. Low flow of the sampling pump can indicate that the battery level is low or that some fines are trapped in the pump or tubing.

The purpose of vapor sampling of the extracted off-gas were to determine mass transfer via volatilization of contaminants and the effects of air sparging on contaminant loading rates in the vadose zone. Where a SVE system is in place, SVE off-gas samples were collected by connecting either an evacuated 1-L Summa polished air-sampling canister or a Tedlar™ bag to the vapor sampling port. Prior to sample collection, the port was flushed with a vacuum pump to ensure that a representative sample was obtained. The evacuated canister was then connected to the sampling port, the valve opened, and a vapor sample collected from the conduit.

Mass transfer rates were assessed using push-pull tests as described in Amerson (1997). The push-pull tests involve the injection of a known mass of substrate such as acetate into a discrete groundwater sampling point. A known volume of groundwater is extracted and the mass of substrate consumed is used to determine biodegradation and mass transfer rates. Full details of these tests are in Amerson (1997).

3.5.2 System Testing

System testing was conducted to make an assessment of the feasibility of air sparging by examining air flow into the aquifer, air distribution around the sparge point, the effectiveness of the soil vapor extraction system, and safety issues. Air flow into the aquifer versus air injection pressure at a sparge point was monitored to evaluate varying pressure requirements necessary to achieve different flowrates into the subsurface. In addition, air injection pressure was monitored to record the minimum air entry pressure to induce flow into an aquifer. The air-entry pressure is heavily dependent on the type of geology at the site.

Dissolved Oxygen**:** Monitoring increases in dissolved oxygen in the saturated zone is one approach in determining the effectiveness of the air sparging system for delivering air to the groundwater treatment zone. Groundwater samples were collected from the discrete groundwater sampling points prior to start up of the air sparging system and periodically during testing. Dissolved oxygen was measured according to the procedure described in the previous section.

Sulfur Hexafluoride (SF_6) Tracer Testing: In these studies, SF_6 was blended with the air injection stream from the in situ air sparging compressor beginning approximately 24 hours after initiation of air sparging. SF_6 was injected continuously at a known mass rate for approximately 24 hours, at which time groundwater samples were collected to assess air distribution within the aquifer. The groundwater samples were collected from the discrete groundwater samplers. The concentration of SF_6 in the injected air was determined in the field. Based on the injection concentration, a theoretical solubility in the groundwater is calculated using a dimensionless Henry's gas constant of 150.

The SF_6 data do not give a direct measure of air saturation. Instead, the SF_6 data indicate where sparge air has been present in the groundwater zone during the period of its injection. In general, it can be assumed that concentrations near saturation indicate that air pathways were near the sampling point (e.g., within 10 to 20 cm based on the volume of groundwater sampled) and that zero or near-zero percent saturations indicate that air has not been in the vicinity of the sampling point.

Pressure Transducer Measurements: Changes in groundwater levels in response to the air sparging were measured using pressure transducers and connected to a data acquisition system. A groundwater pressure transducer (In Situ model SP4000-232 or equivalent) placed in existing groundwater monitoring wells, were used to monitor small fluctuations in the groundwater elevation. The transducer is factory-calibrated and laboratory-tested. The pressure transducer has an accuracy of approximately ±0.05 of full scale operating range. The pressure transducer was checked to ensure proper operation and utilized according to manufacturer's specifications.

Helium Monitoring: The efficiency with which the sparge air is recovered by the SVE system can be determined using a helium recovery test. Helium is injected at a known concentration along with the sparge air. The concentrations of helium in the off-gas are monitored until it stabilizes. The efficiency with which the sparge air is recovered by the soil vapor extraction system can be determined using a helium recovery test. Helium is injected at a known concentration along with the sparge air. The concentrations of helium in the off-gas are then monitored until it stabilizes.

This helium tracer test can also simultaneously be used to evaluate the degree of contaminant volatilization from the saturated zone, as well as determining approximately where air exits the saturated zone by measuring helium concentrations at the discrete vadose zone sampling points.

Helium in the soil gas was measured with a Marks Helium Detector Model 9821 or equivalent with a minimum sensitivity of 100 ppmv (0.01%). The helium detector is factory calibrated, but its accuracy is checked in the field with a standard to ensure proper operation.

4.0 PERFORMANCE ASSESSMENT

The data collected as part of this study was used to refine and improve the Air Sparging Design Paradigm. Data was collected and/or evaluated from ten field sites. The primary objective at each site was to implement portions of the Air Sparging Design Paradigm as appropriate and determine whether the activities recommended in the Air Sparging Design Paradigm were valid and generated the necessary information to determine the feasibility of air sparging at the site. A summary of the data collected is provided in this section. Additional details are provided in the Final Report.

The level-of-effort at the 10 field sites varied depending on the scope of the project. At one site (NBVC, Port Hueneme Site, CA), a full-scale air sparging system was installed based on the Standard Design Approach described in the Air Sparging Design Paradigm. At four sites, extensive diagnostic tests were conducted (Cape Canaveral AS, FL; Eielson AFB, AK; Fairchild AFB, WA; and Fort Lewis, WA). At five sites, minimal diagnostic testing was conducted (Camp Lejeune, SC; Camp Pendleton, CA; DoDHF Novato, CA; Hill AFB, UT; and McClellan AFB, CA).

The pilot test recommended in the Air Sparging Design Paradigm for the Standard Design Approach prescribes a suite of diagnostic tests to assess air distribution. The recommended diagnostic tests include pressure response testing, deep vadose zone helium tracer testing, and dissolved oxygen monitoring. Data collected for this study ahs emphasized the necessity of a suite of diagnostic tests, rather than a reliance on one type of testing. For example, pressure response testing at Camp Pendleton, CA indicated that the subsurface geology was stratified, possibly causing poor treatment of the target treatment zone. However, results of deep vadose zone helium tracer testing indicated that the injected air was contacting the groundwater within a small zone around the injection well.

The diagnostic tests also proved useful to evaluate existing systems in terms of their effectiveness at treating the target treatment zone. Three of the sites investigated (Eielson AFB, AK; Fairchild AFB, WA; and Fort Lewis, WA) had air sparging systems that were not impacting the entire target treatment zone and therefore were operating inefficiently. Conversely, the air sparging system installed at Cape Canaveral AS, FL was shown to be functioning efficiently and as designed.

The Standard Design Approach recommended in the Air Sparging Design Paradigm prescribes a 15-ft well spacing. At all sites were a zone of influence was determined, this well spacing would have been sufficient to achieve adequate treatment of the target treatment zone. At the majority of sites, air was observed to impact groundwater within a small radius around the injection well.

A final observation from this study was that many air sparging systems were poorly instrumented and monitored to the extent that the system performance was compromised. It is critical that the system be properly instrumented so that flow to each individual air injection well can be verified and measured. In addition, groundwater quality data obtained from conventional monitoring wells can be compromised by air sparging system operation. In such cases, practitioners often observe rapid increases in dissolved oxygen levels and rapid declines in dissolved contaminant

concentrations. Then, after system operation, contaminant concentrations may rebound to near pre-treatment levels; in some cases, this rebound may occur over periods of 1 to 12 months. Thus, one must be cautious when interpreting monitoring well data at air sparging sites. To help minimize the potential for errors, Johnson et al. (1997) suggest: a) long-term (12 months) monitoring following system shut-down, b) use of discrete (narrowly-screened) sampling installations, or c) short-term (12 to 24 h) continuous slow-purging of conventional monitoring wells (or discrete sampling points) with time-series sampling.

5.0 COST ASSESSMENT

This section discusses the cost considerations involved in the application of air sparging. Discussed in the following sections are cost reporting for the demonstration and for a real-world application of the demonstration, a cost analysis, and a cost comparison.

5.1 COST REPORTING

This project involved the analysis of data from 10 existing air sparging systems. At one site, Port Hueneme, CA, a pilot-scale air sparging system had previously been installed and, as part of this project, a full-scale system was installed according to the guidelines defined in the Air Sparging Design Paradigm. Since this was the only site in which a full-scale system was installed, the demonstration costs for this site are reported. Costs are compared for the actual demonstration costs and a real-world implementation of air sparging at this site.

5.1.1 Actual Project Costs at Port Hueneme, CA

The site at Port Hueneme is a gasoline-contaminated site located in the source zone. Groundwater is located at a depth of approximately 9 to 10 ft bgs, with the contaminated portion of the aquifer located from the groundwater table down to approximately 15 ft bgs. The area of the plume that contains near-saturation levels of petroleum hydrocarbons is quite large; therefore, the full-scale system was installed in a smaller portion of the plume, in an area approximately 60 ft by 75 ft. The air sparging system was operated for approximately 18 months.

Listed below is a description of the equipment installed at the site and the activities conducted. Any unique features of the equipment or activity are discussed.

- Site characterization activities were conducted several years prior to the start of this project. Activities included groundwater sampling, soil sampling, and analysis of soil borings for soil heterogeneities. Groundwater samples were analyzed in the field using a field gas chromatograph. Approximately 100 soil samples were collected and sent for analysis at an analytical laboratory.

- Twelve 14-level multi-level samplers were installed using the VibraCore direct-push technique. The sampling intervals were installed in a 2-inch-diameter schedule 80 PVC riser. Each sampling interval consisted of ⅛-inch stainless steel tubing with a ⅛-inch Swagelock fitting at the end. The stainless steel tubing was covered with polyvinyl tubing to insulate them from each other. The stainless steel tubing was bent so that the Swagelock fitting terminated at a 100-mesh stainless steel screen that was PVC-welded to the PVC riser. Sampling intervals were installed at each multi-level sampler with the Swagelock fitting at the following depths bgs: 2, 4, 6, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19 ft.

- 18 air injection wells were installed. The 2-inch-diameter sparge wells were installed to a depth of approximately 20 ft (6.1 m) bgs with approximately 2 ft (1.2 m) of 10-slot

schedule 40 PVC screen and 19 ft (5.8 m) of PVC casing finished 1 ft (0.30 m) above grade. A silica sand and filter pack was installed across the screened interval and bentonite pellets were used to fill the remaining annular space to grade. The bentonite pellets were frozen prior to use for installation below the water table.

- Four 1-inch-diameter PVC directional soil vapor extraction wells were installed. The wells were installed to a total depth of 10 ft (3.0 m) with 5 ft (1.5 m) of 10-slot screen and 6 ft (1.8 m) of casing. The annular space outside the screened interval of the monitoring wells was filled with a medium-grade silica sand filter pack. The remaining annular space was sealed to the surface with a bentonite plug.

- Six groundwater monitoring wells were installed. The monitoring wells were installed to a total depth of 20 ft (6.1 m) with 15 ft (4.6 m) of 10-slot screen and 6 ft (1.8 m) of casing. The annular space outside the screened interval of the monitoring wells was filled with a medium-grade silica sand filter pack. The remaining annular space was sealed to the surface with a bentonite plug.

- System monitoring was conducted twice a week. This monitoring schedule is more frequent than would be needed for a remediation project.

- The system was operated for 18 months. Approximately 50 final soil samples were collected.

Table 3 lists demonstration costs for the project at Port Hueneme, CA. The total cost for the demonstration at this site was \$189,880, at a cost of \$130/yd^3.

5.1.2 Costs Associated with a Real-World Implementation of Air Sparging at Port Hueneme, CA

There are a number of differences between the actual demonstration costs and a real-world implementation of air sparging at CBC Port Hueneme, CA. A summary of the assumptions for a real-world implementation of air sparging at the CBC Port Hueneme site are discussed below:

- Site characterization includes an evaluation of site geology/hydrogeology, site soils/surface hydrology, nature and extent of contamination, and generation of a Remedial Investigation report. The number of groundwater and soil samples is significantly smaller than that collected during the demonstration.

- Pilot testing as prescribed by the Air Sparging Design Paradigm is conducted.

- Installations include 18 air injection points, nine single-level groundwater monitoring points, nine single-level soil gas monitoring points, 14 soil vapor extraction wells, and three groundwater monitoring wells.

- A soil vapor extraction system is installed and operated for six months.

Table 3. Port Hueneme, CA Demonstration Costs.

Cost Category	Sub Category	Costs ($)
FIXED COSTS		
1. CAPITAL COSTS	Site characterization activities • Soil sampling • Groundwater sampling • Travel	 $12,500 $1,200 $1,200
	Pilot testing • Equipment and materials • Labor and miscellaneous costs • Travel	 $1,760 $10,000 $3,000
	Full-scale air sparging equipment cost • Air compressor • Installation of 18 air injection points • Flow meters, pressure gauges, piping, & miscellaneous equipment • Labor and miscellaneous costs • Travel	 $20,250 $6,750 $6,530 $14,800 $5,000
	Soil vapor extraction equipment[1]	$6,200
	Start-up and testing	$11,000
	Final soil sampling	$12,500
		Sub-Total: $112,690
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Daily maintenance checks for 18 months	$12,600
	Monthly site cleanup	$20,160
	Utility costs for 18 months	$21,120
	Quarterly groundwater sampling for 18 months	$3,260
	Materials and consumables	$3,900
	Final site cleanup	$16,150
		Sub-Total: $77,190
TOTAL COSTS		
		TOTAL TECHNOLOGY COST: $189,880
		Quantity Treated[2]: 1,500 yd^3
		Unit Cost ($): $130/$yd^3$

[1] The soil vapor extraction unit was only operated for a few days due to difficulties with water extraction, resulting in the low operating cost.

[2] Quantity treated was estimated based on a contaminated interval from 5 to 15 ft bgs, and an area of approximately 60 ft by 75 ft.

- A weekly maintenance check is conducted.
- Quarterly groundwater sampling is conducted.
- The air sparging system is operated for a two-year period.

Costs for a real-world implementation at the CBC Port Hueneme CA site are shown in Table 4. The cost for year two of operation is discounted using present value (PV) or discounted cashflow analysis. PV cost represents the amount of money that would have to be set aside today to cover all the capital investment and O&M costs occurring in the present and future.

$$PV_{technology} = \text{Capital Investment} + PV_{\text{annual O\&M costs over life of the new technology}} \qquad (5\text{-}1)$$

In the above equation, capital investment does not have to be discounted back to the present because this investment occurs immediately (time t=0). The term $PV_{\text{annual O\&M costs over life of the new technology}}$ represents the annual O&M costs (and savings realized, if any) over several years of operation, adjusted for the time value of money. This adjustment is done by dividing each year's O&M costs by a factor that incorporates a discount rate (r), as shown in Equations 5-2 and 5-3. The discount rate incorporates the combined effect of inflation, productivity, and risk. In other words, the discount rate accounts for the fact that any cost that is postponed into future years frees up money that can be put to productive use and provides a rate of return equal to the discount rate (r).

$$PV_{\text{annual O\&M costs}} = \sum \frac{\text{O \& M cost in Year t}}{(1+r)^t} \qquad (5\text{-}2)$$

$$PV_{\text{annual O\&M costs}} = \frac{\text{O \& M cost in Year 1}}{(1+r)^1} + \frac{\text{O \& M cost in Year 2}}{(1+r)^2} + \ldots \frac{\text{O \& M cost in Year n}}{(1+r)^n} \qquad (5\text{-}3)$$

A real discount rate of 2.9% is currently recommended in the PV analysis, as per the 1999 update to the U.S. EPA Office of Management and Budget (OMB) circular (U.S. EPA, 1993). The total cost to operate the air sparging system for a two-year period is \$268,490 at a cost of \$179/yd^3.

5.2 COST ANALYSIS

When implementing air sparging, the major cost drivers are (1) the soil characteristics or in situ heterogeneity and (2) the necessity of operating soil vapor treatment. Soil characteristics impact air sparging primarily by affecting air distribution. Air distribution can impact project costs in a number of ways.

- Permeable aquifer soils result in a smaller than expected zone of influence; therefore, additional wells are needed to ensure adequate air/contaminant contact.
- Layering of varying permeabilities of soils will likely result in air not contacting portions of the aquifer and again, additional wells may need to be added at a later date to treat portions of the site not receiving air.
- Poor air/contaminant contact caused by unpredictable air distributions can result in poor treatment, and necessitate operation of the air sparging system for longer than predicted.

Table 4. Real-World Costs for Conducting Air Sparging at Port Hueneme, CA.

Cost Category	Sub Category	Costs ($)
FIXED COSTS		
1. CAPITAL COSTS	Site characterization activities[1]	$55,000
	Pilot testing[2] • Equipment and materials • Labor and miscellaneous costs	 $12,200 $10,200
	Data evaluation, engineering design, Design Plan, procurement of subcontractors, interactions with regulators[3]	$16,700
	Utility clearance; arrangements for equipment/media storage & debris disposal[3]	$4,200
	Full-scale air sparging equipment cost • Air compressor[3] • Installation of 18 air injection points[4] • Flow meters, pressure gauges, piping, & miscellaneous equipment[4]	 $20,250 $6,190 $5,000
	SVE equipment and operation cost[5]	$76,550
	Start-up and Testing[3]	$2,700
		Sub-Total $147,440
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Weekly maintenance check for one year[3]	$2,800
	SVE operation and maintenance cost (first year)	$61,550
	Annual utility cost[6]	$22,800
	Quarterly sampling for one year	$4,600
	Final soil sampling	$4,600
		Sub-Total Year 1: $91,750
		Sub-Total Year 2: $29,300
		TOTAL TECHNOLOGY COST $268,490
		Quantity Treated[7]: 1,500 yd^3
		Unit Cost ($): $179/$yd^3$

1 Costs estimated using RACER 2000. Includes costs for evaluation of site geology/hydrogeology, site soils/surface hydrology, nature and extent of contamination, and generation of a Remedial Investigation report.

2 Costs estimated based on contractor quotes. Costs are based on conducting a pilot test using the Standard Design Approach described in the Air Sparging Design Paradigm. Assumes that equipment installation and testing are completed in two weeks, and that helium and pressure monitoring equipment are rented.

3 Actual cost of compressor used for demonstration.

4 Cost estimated based on contractor quote.

5 Cost estimated using RACER 2000. Assumes a 6-month operation time given that vapor concentrations are likely to decrease substantially within the first 6 months of operation.

6 Assumes a 93% efficiency for the motor, a 97% run time, and a utility rate of $0.1116/kw-hour (California rates).

7 Quantity treated was estimated based on a contaminated interval from 5 to 15 ft bgs, and an area of approximately 60 ft by 75 ft.

These situations result in not only additional costs for wells, but additional costs for blower capacity and mobilization/demobilization costs. The air distribution issue is difficult to address from just examining soil boring logs. Pilot testing is necessary to evaluate the air distribution at a site, and since the pilot test cannot cover the whole site, fine-tuning of air injection well installations may be necessary.

The following four scenarios illustrate the impact of different cost factors on the total project cost.

- Scenario 1: Typical air sparging installation that functions as expected (Table 4).
- Scenario 2: Air distribution is poor; installation of additional air injection wells to improve air distribution.
- Scenario 3: Air distribution is poor; must operate system longer than intended because of poor air distribution.
- Scenario 4: Vapor collection and treatment is not required due to the absence of receptors within the air sparging zone of influence.

Under Scenario 1, the total project cost is \$268,490 or \$179/yd^3. The remaining three scenarios are based upon this initial cost. A cost summary is shown in Table 5.

Under Scenario 2, additional injection wells are required to improve air distribution. If we assume that 9 additional injection wells are required (50% more wells), additional costs are incurred for data evaluation and engineering design, construction and material cost for 9 additional wells, and associated equipment such as flow meters and pressure gauges. It is assumed that additional compressor capacity is not required, since the additional nine wells would be worked into the pulsed injection scheme. Additional costs for these items are \$10,270. This amount is in addition to the base total project cost of \$268,490, resulting in a total project cost of \$278,760 or \$186/yd^3. This represents a cost increase of approximately 4%.

Under Scenario 3, poor air distribution required a longer operation period than originally planned. For one additional year of operation, additional costs would be \$28,500 with a total project cost of \$296,990 or \$198/yd^3. This represents a cost increase of approximately 11%. For two additional years of operation, additional costs would be \$56,200 with a total project cost of \$324,690 or \$216/yd^3. This represents a cost increase of approximately 22%.

Under Scenario 4, it is assumed that no soil vapor extraction system is required during operation of the air sparging system given that no receptors exist within the zone of air sparging. This would result in a decrease in the total project cost by \$76,550, to give a total project cost of \$191,940 or \$128/yd^3. This represents a cost decrease of approximately 30%.

Comparison of these scenarios demonstrates that the installation and operation of soil vapor extraction in conjunction with air sparging will have the most significant cost impact. SVE systems have often been routinely installed with air sparging systems, whether or not receptors are at risk. This exercise demonstrates the importance of carefully evaluating the need for an SVE system.

Table 5. Cost Impact of Various Design Parameters.

Scenario	Parameter		Total Cost ($)	Unit Cost[1] ($/yd^3)
1	Standard installation (Table 4)		$268,490	179
2	• Data evaluation, engineering design • Installation of 9 air injection wells • Associated flow meters, pressure gauges, piping & miscellaneous equipment	$4,100 $3,670 $2,500	$278,760	186
3	Additional one year of operation Additional two years of operation	$28,500 $56,200	$296,990 $324,690	198 216
4	Operation without SVE	($76,550)	$191,940	128

[1] Quantity treated was estimated based on a contaminated interval from 5 to 15 ft bgs, and an area of approximately 60 ft by 75 ft.

Secondly, the costs associated with long-term monitoring can have a significant cost impact and outweighs the costs associated with the installation of additional injection wells. This exercise supports the standard design approach described in the Air Sparging Design Paradigm of installing closely spaced wells for optimum performance. Higher capital costs associated with air injection wells will be offset by shorter clean-up times.

Finally, Scenario 2 demonstrated that even with a significant number of additional injection wells installed, the cost impact was minimal. The cost associated with the installation of the additional air injection wells is quite small if it results in a shorter remediation time.

5.3 COST COMPARISON

Air sparging has become the most practiced engineered in situ remediation option when targeting the treatment of hydrocarbon-impacted aquifers. The most common installation is for remediation of petroleum hydrocarbon source zones. Therefore, this section examines costs associated with remediation of a petroleum hydrocarbon source zone. As mentioned, air sparging would likely be the first remedial alternative considered. However, practitioners have also implemented removal of the contaminated soil and groundwater with installation of sheet piling to prevent further plume development as a more rapid remedial alternative than air sparging.

The cost basis for this site is shown in Table 6. The site is similar to that discussed in Sections 5.1 and 5.2, with only a slight difference in depth to water and the base of contamination. Based on these site parameters, the cost for soil and groundwater removal with sheet piling installation is shown in Table 7. The total project cost for this remedial alternative is $900,266 with a unit cost of $474/yd^3. Total remediation time is estimated at approximately 10 weeks.

Using the same cost basis, the cost for installation and operation of an air sparging system is shown in Table 8. The total project cost for this remedial alternative is $268,250 with a unit cost of $141/yd^3. Total remediation time is estimated at approximately two years.

In comparison to soil removal with sheet piling installation, air sparging systems offers substantially lower capital costs. However, the total remediation time for operation of an air sparging system is longer than for soil removal and sheet piling installation.

Table 6. Basis for Air Sparging and Thermal Treatment Cost Estimate.

Parameter	Value
Soil type	Sandy till
Hydraulic conductivity	<1 ft/day
Contaminant type	BTEX (100 mg/L [max]) and naphthalene (2.5 mg/L [max])
Contaminated area	5,000 ft^2
Depth to groundwater	18 ft
Depth to base of groundwater contamination	24 ft
Expected treatment period (air sparging)	2 yr
Expected treatment period (thermal treatment)	10 weeks

Table 7. Implementation Costs for Soil Removal with Sheet Piling Installation.

Cost Category	Sub Category	Costs ($)
	FIXED COSTS	
1. CAPITAL COSTS	Site characterization activities[1]	$55,000
	Mobilization[2]	$2,760
	Surveying[2]	$2,122
	Tank and soil removal and disposal[2]	$43,284
	Sheet piling installation[2]	$760,000
	Demobilization and final reporting[3]	$32,500
		Sub-Total $895,666
	VARIABLE COSTS	
2. OPERATION AND MAINTENANCE	Final sampling[3]	$4,600
		TOTAL TECHNOLOGY COST $900,266
		Quantity Treated: 1,900 yd^3
		Unit Cost ($): $474/$yd^3$

1 Costs estimated using RACER 2000. Includes costs for evaluation of site geology/hydrogeology, site soils/surface hydrology, nature and extent of contamination, and generation of a Remedial Investigation report.
2 Costs estimated based on contractor quotes.
3 Cost estimated using RACER 2000.

Table 8. Air Sparging Costs for the Cost Basis Shown in Table 6.

Cost Category	Sub Category	Costs ($)
FIXED COSTS		
1. CAPITAL COSTS	Site characterization activities[1]	$55,000
	Pilot testing[2] • Equipment and materials • Labor and miscellaneous costs	 $13,200 $10,200
	Data evaluation, engineering design, Design Plan, procurement of subcontractors, interactions with regulators[3]	$16,700
	Utility clearance; arrangements for equipment/media storage & debris disposal[3]	$4,200
	Full-scale air sparging equipment cost • Air compressor[3] • Installation of 27 air injection points[4] • Flow meters, pressure gauges, piping, & miscellaneous equipment[4]	 $11,100 $12,100 $7,000
	SVE equipment and operation cost[5]	$76,550
	Start-up and Testing[3]	$2,700
		Sub-Total $208,750
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Weekly maintenance check for one year[3]	$2,800
	Annual utility cost[6]	$22,800
	Quarterly sampling for one year	$4,600
		Sub-Total Year 1: $30,200
		Sub-Total Year 2: $29,300
		TOTAL TECHNOLOGY COST $268,250
		Quantity Treated[7]: 1,900 yd^3
		Unit Cost ($): $141/$yd^3$

1 Costs estimated using RACER 2000. Includes costs for evaluation of site geology/hydrogeology, site soils/surface hydrology, nature and extent of contamination, and generation of a Remedial Investigation report.

2 Costs estimated based on contractor quotes. Costs are based on conducting a pilot test using the Standard Design Approach described in the Air Sparging Design Paradigm. Assumes that equipment installation and testing are completed in two weeks, and that helium and pressure monitoring equipment are rented.

3 Cost estimated using RACER 2000.

4 Cost estimated based on contractor quote.

5 Cost estimated using RACER 2000. Assumes a 6-month operation time.

6 Assumes a 93% efficiency for the motor, a 97% run time, and a utility rate of $0.1116/kw-hour (California rates).

7 Quantity treated was estimated based on a contaminated interval from 14 to 24 ft bgs, and an area of approximately 5,000 ft^2.

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6.0 IMPLEMENTATION ISSUES

The implementation issues discussed in this section are based upon general implementation of air sparging, not on this specific project. This was done because this project involved the optimization of air sparging pilot testing and design, not a thorough installation and design of a single system; therefore, this section would be of most benefit as a general discussion of air sparging implementation issues.

6.1 COST OBSERVATIONS

The key factors that impact air sparging project costs are:

- Area of groundwater contamination;
- Depth to groundwater;
- Depth to base of groundwater contamination;
- In situ heterogeneity;
- Treatment period; and
- Vapor collection and treatment.

As can be seen from this list of parameters, the factors that impact project costs are very site-specific. Parameters such as the area of groundwater contamination, depth to groundwater, and depth to the base of groundwater contamination are fixed once site characterization is completed, and typically will not change significantly once the air sparging system is installed.

In contrast, the in situ heterogeneity can impact project costs and cause them to differ from original predictions once air sparging is initiated. While pilot testing is useful to evaluate portions of the site, the practitioner must be aware that in situ heterogeneities will exist throughout the site and could impact air distribution to the point that additional system engineering may be required after installation to ensure that the target treatment zone is adequately treated. The Standard Design Approach was developed to avoid this problem, by prescribing close well spacings to provide the maximum possibility of success.

The total treatment period also is difficult to predict in advance. If an air sparging system must be operated for longer than predicted, the cost of additional monitoring for a 2-year period can be significant, particularly if air extraction and treatment must be conducted during this time. The practitioner can make reasonable estimates based on past performance; however, this is an uncertainty in project costs.

6.2 PERFORMANCE OBSERVATIONS

The primary performance criterion for air sparging systems is reduction of groundwater contaminant levels. For source zone or plume treatment, contaminant levels are monitored within the target treatment zone and monitoring should continue at least one year after system shutdown to ensure that contaminant levels do not rebound. The practitioner should leave the air sparging system infrastructure in place during this time in the event it is necessary to re-initiate

air sparging. If the air sparging system is used for plume containment in the form of an air sparging curtain, down-gradient contaminant levels must be below regulatory limits.

The secondary performance criterion is air flowrates. Air flowrates must be monitored regularly to ensure that air flow is maintained at the design injection rate. Flowrates can vary due to fluctuations in water levels or moisture content in soils. If flowrates decrease significantly, the target treatment zone will not receive sufficient air contact resulting in poor performance. Weekly system checks should be made so that flowrates can be adjusted as necessary.

6.3 LESSONS LEARNED

In a recent survey of air sparging system design and operations at Department of Defense (DoD) facilities, the authors observed that many air sparging systems were poorly instrumented and monitored. Based on this work and other experience, it is not unreasonable to conclude that a significant fraction of existing air sparging systems are improperly instrumented and monitored. In particular, users should be aware of the following:

- It is critical that the system be properly instrumented so that flow to each individual air injection well can be verified and measured. It is the authors' experience that many systems do not have this level of instrumentation. Quite frequently systems have a single flow measurement for an entire manifold of air injection wells. In those systems, one cannot determine the flow to each well, or even if there is flow to a given well in a multiple well system (unless only one well operates at a given time during normal system operation). It is the authors' experience that, in systems containing injection wells sharing a common manifold, all the air may be flowing to only a few of the manifolded wells. As discussed in Johnson et al. (2001), it is the combination of variations in screened intervals, variations in soil properties, and the nature of air flow - injection pressure relationships that leads to this common problem. Thus, individual flow meters, pressure gauges, and valves are critical to proper air sparging system operation.

- As illustrated by Johnson et al. (1997), groundwater quality data obtained from conventional monitoring wells can be compromised by air sparging system operation. In such cases, practitioners often observe rapid increases in dissolved oxygen levels and rapid declines in dissolved contaminant concentrations. Then, after system operation, contaminant concentrations may rebound to near pre-treatment levels; in some cases, this rebound may occur over periods of 1 to 12 months. Thus, one must be cautious when interpreting monitoring well data at air sparging sites. To help minimize the potential for errors, Johnson et al. (1997) suggest: a) long-term (12 months) monitoring following system shut-down, b) use of discrete (narrowly-screened) sampling installations, or c) short-term (12 to 24 h) continuous slow-purging of conventional monitoring wells (or discrete sampling points) with time-series sampling. With respect to the latter, it has been observed that short-term continuous purging eventually yields samples that are more representative of formation conditions than in-well conditions, and that this might replace the need for longer-term groundwater quality monitoring.

During continued air sparging system operation, it is typically observed that volatilization removal rates decline to low (and often non-detect) levels (e.g., see Johnson et al., 2001). At that point it is difficult to assess real-time system performance via traditional measurements (e.g., groundwater monitoring, SVE off-gas sampling, etc.). In those cases, if real-time assessment is important, users should consider the tracer-based tests utilized by Amerson et al. (2001) and Bruce et al. (2001).

6.4 END-USER ISSUES

The air sparging technology has been widely applied for many years at DoD installations. Unfortunately, design practices have varied widely and performance has varied as well. This study has finalized the Air Sparging Design Paradigm in an effort to provide to air sparging practitioners and Base environmental managers a single document providing well-tested design guidance. The air sparging technology has already gained fairly widespread acceptance. This document will provide more Base environmental managers with a more standardized approach by which they can evaluate air sparging design.

6.5 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Air sparging is now well-accepted by regulators and is routinely employed at a number of sites throughout the country. Permitting issues are often involved in the discussion of vapor capture and treatment. While air sparging systems can operate efficiently without vapor capture, SVE systems are often routinely installed in conjunction with air sparging systems. SVE systems are necessary if the subsurface structures or buildings exist within the zone of influence of the air sparging system. However, at those sites where these conditions do not exist, the argument should be made that biological processes in the vadose zone can remove any volatilized contaminants, similar to a bioventing system. The exception is at those sites containing primarily chlorinated solvents. These contaminants may not be biodegraded in the vadose zone, and an SVE system is likely necessary to ensure complete and safe removal of the contaminants.

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APPENDIX A

POINTS OF CONTACT

Point of Contact (Name)	Organization (Name & Address)	Phone/Fax/E-Mail	Role In Project
Lt. Col. Tim Wiley	AFRL/MLQE 139 Barnes Drive Suite 2 Tyndall AFB, FL 32403-5323	(850) 283-6299 (850) 283-6064 timothy.wiley@tyndall.af.mil	Program manager
Dr. Andrea Leeson	Battelle Memorial Institute 505 King Avenue Columbus, OH 43201-2693	(614) 424-5942 (614) 424-3667 leeson@battelle.org	Project Manager
Chris Coonfare	Battelle Memorial Institute 505 King Avenue Columbus, OH 43201-2693	(614) 424-3646 (614) 424-3667 coonfare@battelle.org	Research Scientist
Dr. Paul Johnson	Arizona State University Dept. of Civil Engineering Tempe, AZ 85287-5306	(480) 965-9115 (480) 965-0557 paul.c.johnson@asu.edu	Sub-contractor
Dr. Rick Johnson	Oregon Graduate Institute Dept. of Environmental Science and Engineering PO Box 91000 Portland, OR 97291	(503) 690-1193 (503) 690-1273 rjohnson@ese.ogi.edu	Sub-contractor
Dr. Mike Marley	XDD, LLC 199 Constitution Avenue Bldg 1, Fl4 Portsmouth NH 03801	(603) 433-0191 (603) 431-7807 marley@xdd.llc.com	Sub-contractor
Conrad Christiansen	354 CES/CEVR 2258 Central Avenue Suite 100 Eielson AFB, AK 99702-2299	(907) 377-1678 (907) 377-3367 Christiansoncd@ccgate.eielson.af.mil	Eielson AFB Point of contact
Ernie Lory	NFESC ERD Code ESC414KD 1100 23rd Avenue Port Hueneme, CA 93043-4328	(805) 982-1299 (805) 982-4304 loryee@nfesc.navy.mil	Port Hueneme Point of Contact
Mark Kershner	45 CES/CEVR 1224 Jupiter St Patrick AFB, FL 32925-3343	(407) 853-0964 (407) 853-5435 mark.kershner@pafb.af.mil	Cape Canaveral AFS Point of Contact
Bill Goss	US Army Corps of Engineers CENWS-PM-HW PO Box 3755 Seattle, WA 98124-3755	(206) 764-3267 (206) 764-6795 William.a.goss@usace.army.mil	Fort Lewis Point of Contact
Bruce Oshita	92 CES/CEVR 100 West Ent St. Suite 155 Fairchild AFB, WA 99011-9404	(509) 247-5170 (509) 247-4858 Bruce.oshita@fairchild.af.mil	Fairchild AFB Point of Contact
Nikki Hall	Commanding General ATTN AC/S EMD/IRD Marine Corps Base PSC Box 20004 Camp Lejeune, NC 28542-0004	(910) 451-9610 (910) 451-5997 Hallnl@lejeune.usmc.mil	Camp Lejeune Point of Contact

APPENDIX A

POINTS OF CONTACT (continued)

Point of Contact (Name)	Organization (Name & Address)	Phone/Fax/E-Mail	Role In Project
Tracy Sahagan	Remediation Branch Head Assistant Chief of Staff Environmental Security (AC/S ES) PO Box 555008 Building 22165 MCB Camp Pendleton, CA 92055	(760) 725-9774 (760) 725-9746 Sahagun@pendleton.usmc.mil	Camp Pendleton Point of Contact
Thomas Macchiarella, Jr.	Southwest Division Naval Facilities Eng. Command BRAC Program Office Code 05CA.TM 1230 Columbia St., Suite 1100 San Diego, CA 92101-8517	(619) 532-0907 (619) 532-0940 Macchiarellatl@efdsw.navfac.navy.mil	Department of Defense Housing Facility Novato Point of Contact
Tim Chapman	SM-ALC/EMRP 5050 Dudley Blvd., Suite 3 Building 269E McClellan AFB, CA 95652-1389	(916) 643-0830 ext. 412 (916) 643-5880 chapman.timothy@email.mcclellan.af.mil	McClellan AFB Point of Contact

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

e-mail: estcp@estcp.org
www.estcp.org